Characterization of the Relationship Between the Microstructure and Tensile Strength of Annealed Ti-6Al-4V

Aldo Corona

Senior Project Report

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Advisor

Dr. Blair London

Material Engineering Department

California Polytechnic State University, San Luis Obispo

Approval Page

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Author: Aldo Corona

Date Submitted: June 7, 2011

Prof. Blair London
Faculty Advisor

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Signature

Prof. Trevor Harding
Department Chair

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Signature

Abstract

Tensile coupons of Ti-6Al-4V were heat treated at varying annealing temperatures from 1200°F (648°C) to 1450°F (787°C) at 50°F (23°C) increments for 1 hour. The samples were air cooled to room temperature or furnace cooled to 800°F (426°C) followed by air cooling to room temperature. Four tensile coupons were treated at each annealing temperature and cooling rate. Alpha case was observed to form on the surface of the samples post heat treatment with a maximum depth of 25 µm (.001 in). Samples were tensile tested for their ultimate tensile strength, yield strength, and percent elongation. Samples across all annealing temperatures averaged an ultimate tensile strength of 920 MPa (133 ksi), a yield strength of 880 MPa (127 ksi), and a percent elongation of 15%. These values are higher than the given standards for annealed Ti-6Al-4V by 20 MPa, 50 MPa, and 5%, respectively. This is an offset of 2 to 5% for overall stress, and 50% for elongation. Micrographs of all samples showed equiaxed grains of primary alpha with transformed intergranular beta. The average grain size of primary alpha was 10 µm (4.0×10^{-4} in). These annealing temperatures, which fall under the martensitic starting temperature in the alpha-beta phase field, further relieve residual stresses in the material without compromising the morphology of the alpha-phase. The extent of annealing temperature within this range offers little difference to the strength of the material and microstructure given the hot worked and annealed samples.

KEYWORDS

Materials Engineering, Ti-6Al-4V, annealing, heat treatment, alpha case, tensile testing, metallography

Table of Contents

List of Figures

List of Tables

Introduction

Weber Metals Inc. (Paramount, CA) is a forging company that serves commercial aerospace, electronics, and semi-conductor industries. Weber Metals' exports include forged aluminum and titanium alloys including Ti-6Al-4V, an alloy known for its high strength-to-weight ratio and corrosion resistance.[1] Ti-6Al-4V experiences a series of shaping and heat treatments to meet customer requirements during the forging process provided by Weber Metals. These heat treatments remove residual stresses and achieve specific mechanical properties. Weber Metals has shown interest in the relationship between their forgings' microstructures and tensile strengths as a result of annealing Ti-6Al-4V.

The goal of this project is to characterize the relationship between the microstructure and tensile strength of Ti-6Al-4V across varying annealing temperatures and cooling processes. This involves comparing the effects of the cooling rates to data from tensile tests after given heat treatments. The annealing temperatures range from 1200^{o}F (648^{o}C) to 1450^{o}F (787^{o}C) for 1 hour followed by an air cool or a furnace cool to 800^{o}F (426^{o}C). Industry standards define a full anneal between 1100^{o}F (593^{o}C) and 1350 $\pm 25^{o}$F (732 $\pm 14^{o}$C) at 2 hours with air cooling. This is also known as mill annealing. Mill annealing is the most common heat treatment which merits low strength and moderate ductility of Ti-6Al-4V.[1,2]

Phase Transformations and the β Transus

Titanium is allotropic. It experiences phase transformations at 885^{o}C (1625^{o}F) from Hexagonal Close Packed (HCP), to Body Centered Cubic (BCC). Titanium alloys experience phase changes at varying temperatures which depend on the alloying elements and their concentrations. The phase change is characterized by the phase transformation temperature known as the β transus (Figure 1).[2]

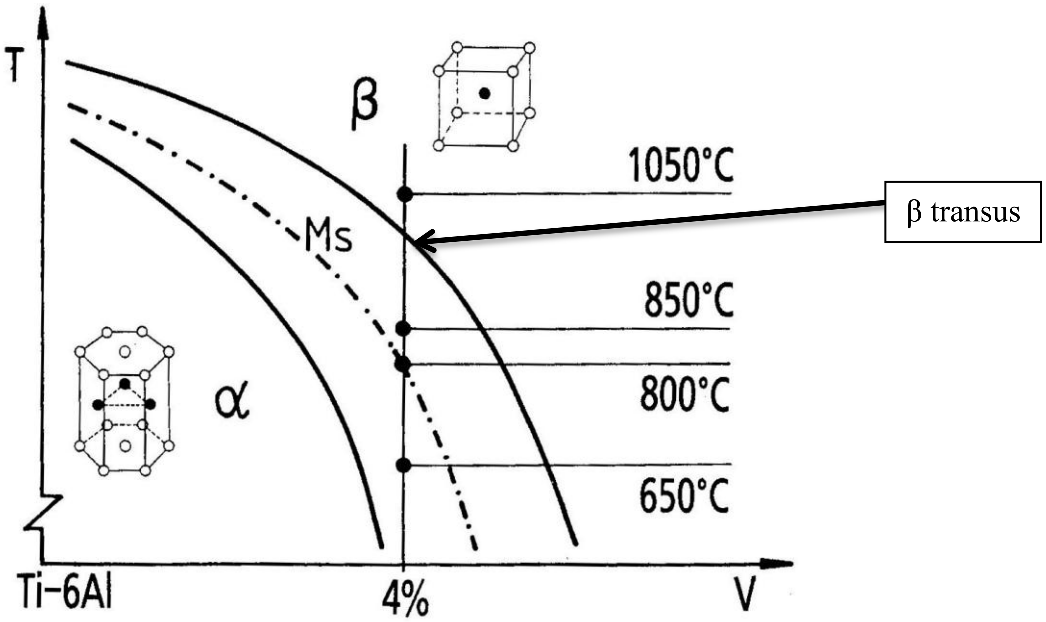

Figure 1: Phase diagram of Ti-6Al-4V with unit cells. The β transus marks the minimum temperature where equilibrium α does not exist.[2]

The β transus temperature is affected directly by alloying components that act as alpha (α) or beta (β) stabilizers. Hydrogen, for example, is a beta stabilizer, which lowers the β transus temperature. Oxygen, nitrogen, and carbon are alpha stabilizers, which increase the β transus temperature. Metal impurities and alloying elements increase or decrease the β transus depending on the element present. Alloying elements are beta stabilizers if their crystal structure is BCC, much like β-phase Ti. These elements include tantalum, molybdenum, niobium, and vanadium. Beta stabilizer elements do not form intermetallic compounds with Ti. Eutectoid systems can be formed with chromium, aluminum, copper, nickel, and other transition metals. These elements have low solubility in α-phase titanium and act as alpha stabilizers. Together, the β transus temperature can be controlled while taking advantage of mechanical properties given with alloys.[3]

The β transus plays a crucial role in determining the microstructure of the alloy. Slow to moderate cooling from above the β transus, for example, leads to the nucleation and growth of α-phase in plate form from β-phase grain boundaries. Slow cooling forms coarse plate-like alpha, whereas air cooling results in finer needle-like α-phase (Figure 2).[2]

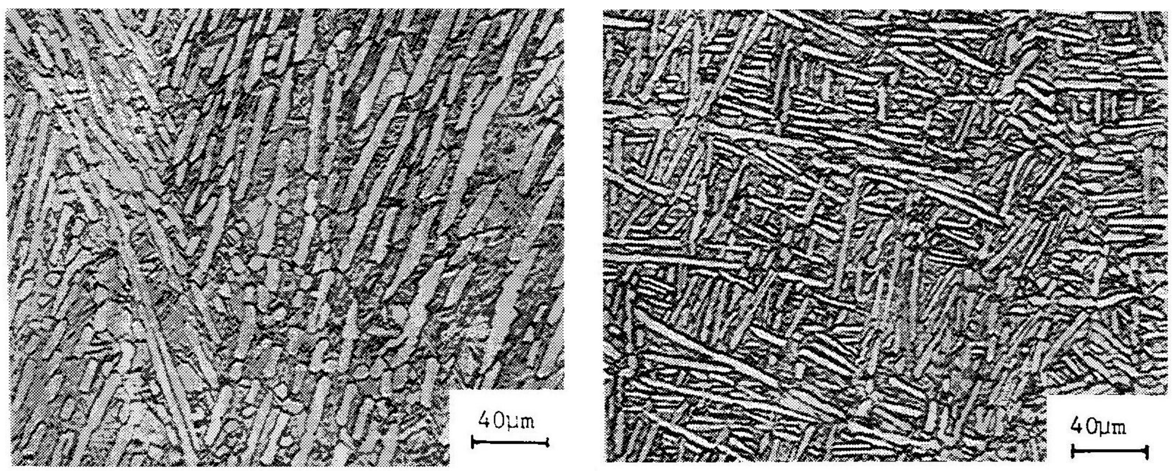

Figure 2: Coarse lamellar structure of α-phase (left). Fine lamellar structure of α-phase (right).[2]

Water quenching from above the β transus transforms β-phase into hexagonal martensite (α′). This form of α-phase is another form of fine needle-like α with high residual stresses. Annealing relieves these stresses to form primary α. Quenching in the α + β phase field above the martensitic transformation temperature will form α′- phase about primary α (Figure 3).[2]

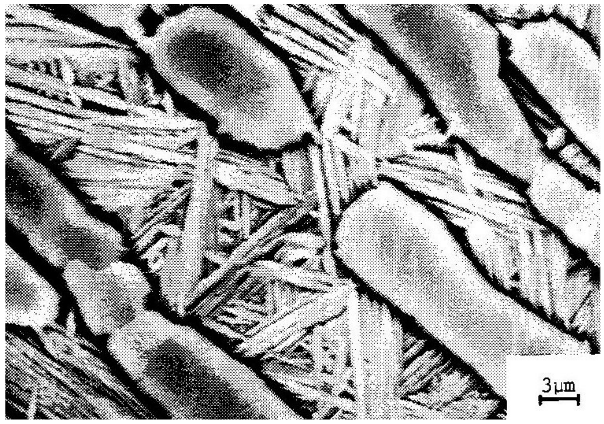

Figure 3: Primary α lamellae surrounded by fine hexagonal martensite **a′.**[2]

Quenching within the α + β phase field below the martensitic transformation temperature yields soft orthorhombic martensite (α″). This phase offers high ductility and low yield strength. Annealing can increase the strength and decrease ductility.[2,3]

Hot working below the β transus in the α + β phase field prevents the coarsening of grains which occurs if only β-phase is present. The resulting microstructure consists of equiaxed grains of α-phase and a volume fraction of transformed β (Figure 4).[2]

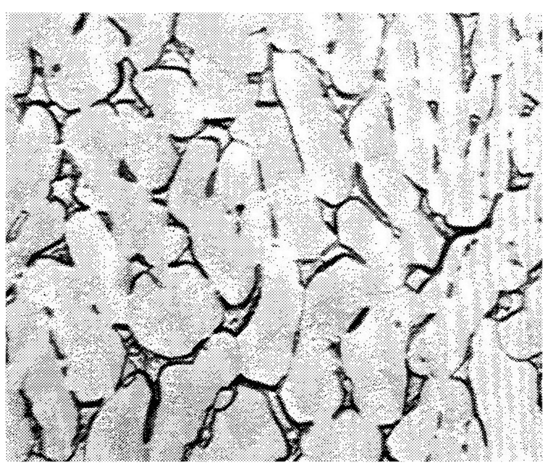

Figure 4: Equiaxed grains of α-phase in hot worked Ti-6Al-4V.[2]

Most forged products have this microstructure after continuous hot working and annealing. Mill annealing provides enough heat to relieve residual stresses without changing the morphology of the α-phase present. This occurs because annealing is done in temperatures below the β transus temperature where the tests for this project will be conducted.[2]

Forging

Ti-6Al-4V is difficult to forge due to flow stress and crack sensitivity when compared with most ferrous alloys. It is less difficult to forge than cobalt- based super alloys. Ti-6Al-4V can be forged with open die and closed die forgings (Figure 5).[2]

Figure 5: 5000 ton open-die press housed at Weber Metals.[4]

In conventional forging, Ti-6Al-4V is pre-heated in a furnace. Once the metal reaches an assigned temperature above or below the β transus temperature, several hundred tons of force is applied to deform the metal into shape. Forgings above the β transus create an acicular α microstructure with high creep resistance. The forging process involves cutting stock into preset blocks, intermediate cleaning of dies, and maintaining a set temperature of the alloy.[2]

Alpha Case

Titanium alloys are susceptible to contamination from oxygen and nitrogen during heat treatments. The result is an oxygen-nitrogen rich phase called alpha-case that is found on the surface of the component (Figure 6).[5]

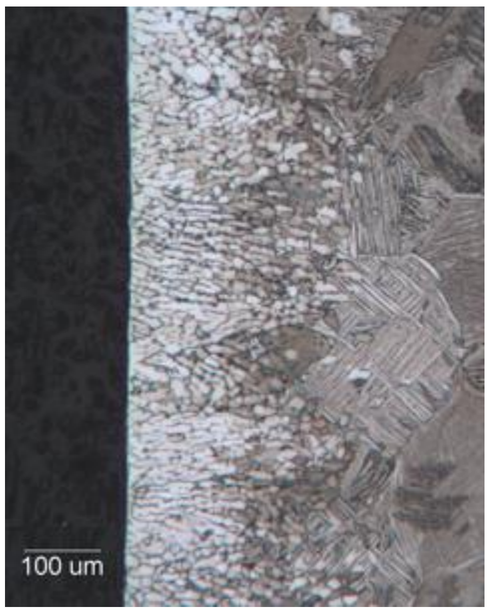

Figure 6: Gradient of oxygen rich alpha case (white) overlapping lamellar α-phase.[5]

This alpha case is highly brittle and is prone to cause microcracking. Alpha case can reduce Ti-6Al-4V performance and fatigue properties. Methods to prevent the formation of alpha case involve vacuum sealed treatments. However, due to cost, most manufacturers rely on grinding or etching a measured layer of alpha case to remove it after treatments.[5]

Broader Impacts

Ti-6Al-4V is a common high strength alloy used in critical applications such as complex airframe structures, space shuttle attachment fittings, compressor cases, missile bodies, gas turbine applications, and hydraulic housings. Many components made of Ti-6Al-4V are made with investment casting (Figure 7).[1]

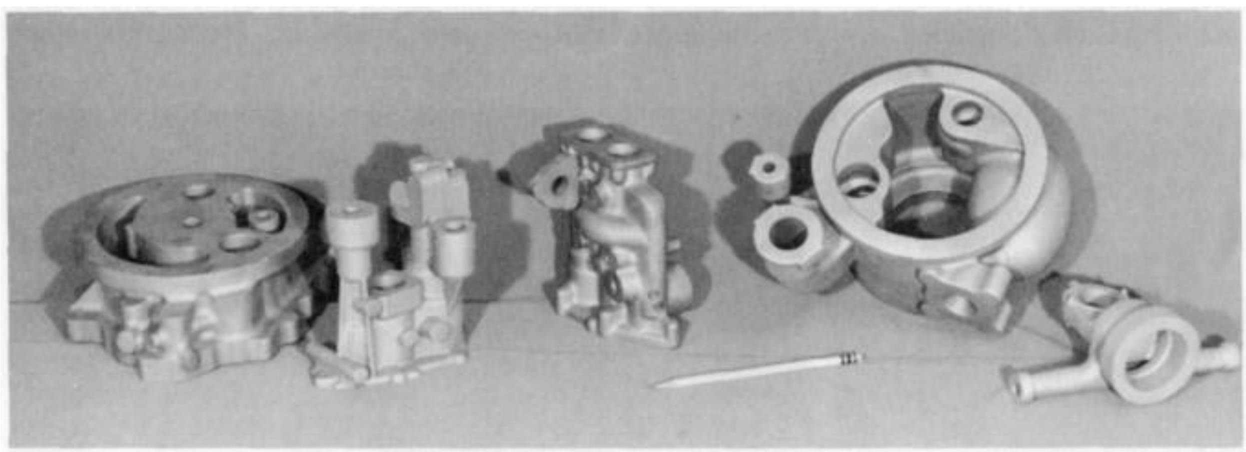

Figure 7: Titanium hydraulic housings produced by investment casting process.[1]

Ti-6Al-4V is the most utilized alloy of the titanium series, making up more than 50% of titanium tonnage in the world. More than 80% of this is used in aerospace, and roughly 3% of it in medical applications.[6] Gas turbine engine components, for example, require alloys that have metallurgical stability at elevated temperatures. This includes low creep rates and low-cycle fatigue, as well as low thermal conductivity. Pressure vessels made of annealed Ti-6Al-4V must have predictable fracture toughness at cryogenic to elevated temperatures. This is controlled by monitoring interstitial elements of oxygen, nitrogen, and carbon to increase ductility and fracture toughness.[7]

The medical applications of Ti-6Al-4V include heart pumps, pacemaker cases, heart-valve parts, and load-bearing bone and hip-joint replacements (Figure 8).[1]

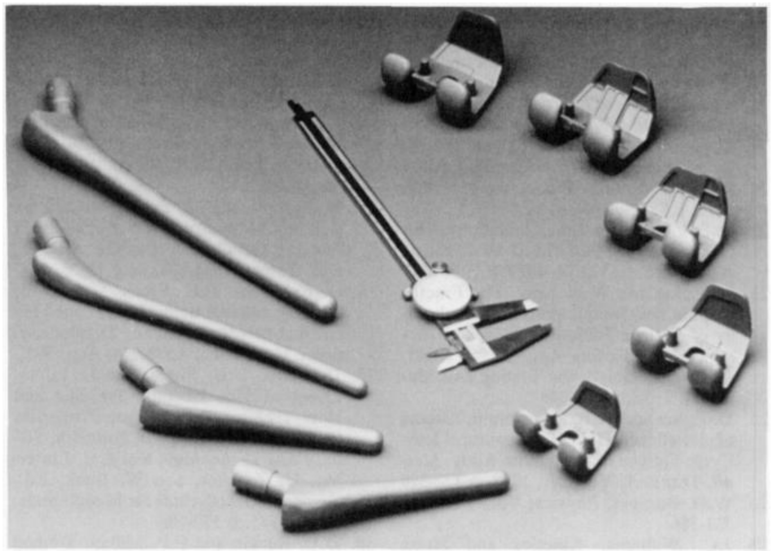

Figure 8: Titanium surgical knee and hip implant prostheses.[1]

This unique set of applications stem from the alloy's high corrosion resistance. Bodily fluids are considered chloride brines that have a pH from 7.4 to the acidic range among other organic acids that do not affect titanium.[7]

Experimental Procedure

The procedures involved in relating the tensile strengths to microstructures include heat treatments, tensile tests, and metallography. An assessment of the furnaces used was required prior to testing to prevent undesired and inaccurate heat treatments.

Testing Furnaces for Maximum Service Temperature

To ensure proper functionality of furnaces, each was tested to ensure it met required service temperatures. To do this, two Fisher Scientific furnaces were set at temperatures above 900°C (Figure 9).

Figure 9: Fisher Scientific isotemp basic muffle furnaces in the Cal Poly Materials Engineering Department heat treatment laboratory.

900°C is not the maximum service temperature of the furnaces, but it clears the maximum temperature required for annealing by at least 100°C. The temperatures were monitored and compared using the furnace's thermocouple display and with a type K thermocouple donated from Weber attached to an Omega HH147U data logger. The thermocouple was positioned near the center of the floor of the furnace.

Furnace Survey

Each furnace was surveyed to map the temperature gradient experienced when the furnace is on. Surveying was conducted using four type K thermocouples attached to an Omega HH147U data logger, mapping four points inside the furnace (Figure 10).

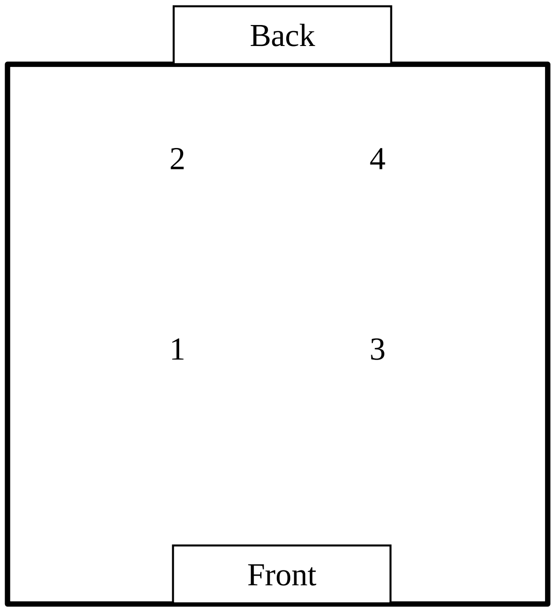

Figure 10: Overhead schematic of furnace survey indicating the locations of the thermocouples.

Each number indicates a point where a thermocouple was positioned for the survey. Thermocouples were bent to shape and rested along the floor of the furnace. Activity of the furnace door did not move the thermocouples as they were secured along the front of the furnace using duct tape. Spacing of the thermocouples was selected to reflect the area where the gauge lengths of the tensile coupons would experience heat treatment. Points 1 and 3 were positioned near the center of the furnace while points 2 and 4 were near the back wall of the furnace. It was advised to stay at least 5 inches clear from the furnace door as significant heat loss occurs near the furnace door.

As Received Sample Analysis

Samples received from Weber Metals included forty-eight mill annealed tensile test coupons and twelve micro samples. Eleven of the twelve micro samples were pre-mounted in bakelite for metallography.

One of the as received pre-mounted samples was polished according to standard up to a 0.5 micron diamond suspension, followed with etching using Kroll's reagent. Images were taken of the microstructure.

Measuring Alpha Case

A build-up of alpha case on the surface of the samples could affect the tensile strength of the coupons. A measurement of the greatest possible depth of alpha case was to be taken for future reference for post-annealing machining. A micro sample of Ti-6Al-4V was placed in the furnace and heated to 800°C (1472°F) for 1 hour and left to furnace cool. The sample was then mounted in bakelite, ground, and polished to 0.5 micron diamond suspension. Etching using Kroll's reagent exposed the depth of alpha case that formed.

Tensile Coupon Heat Treatment

Heat treatments were conducted on forty-eight tensile test coupons. Half of the samples experienced air cooling to room temperature. The other samples were furnace cooled to 800 ^{o}F (426^{o}C), followed by air cooling to room temperature. Groups of four coupons were annealed from 1200^{o}F (648^{o}C) to 1450^{o}F (787^{o}C) for 1 hour. Tensile coupons were arranged vertically on alumina risers (Figure 11).

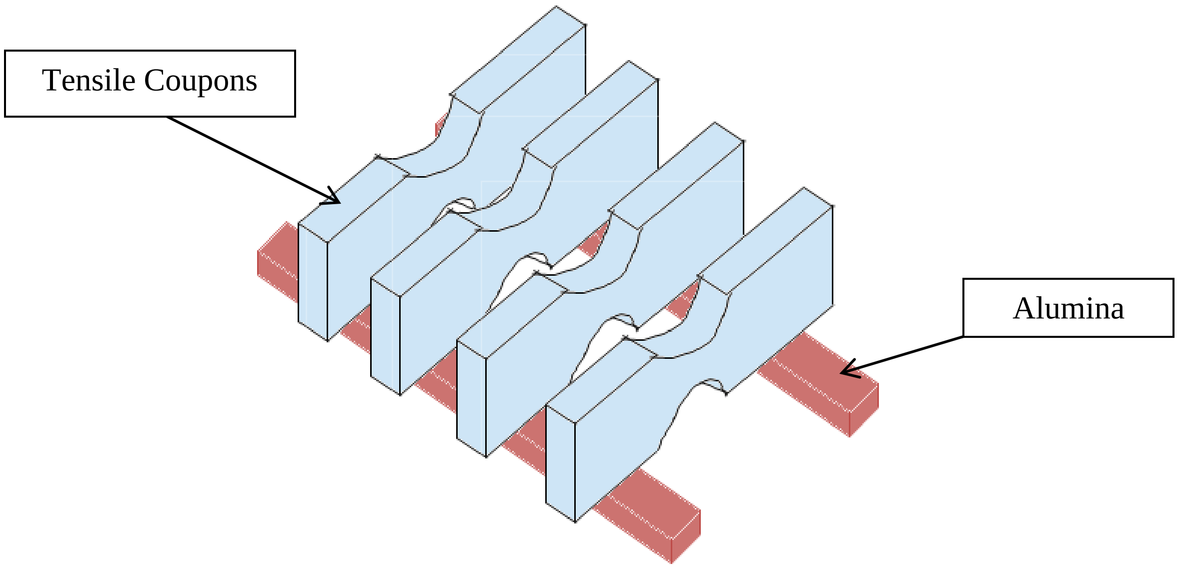

Figure 11: Tensile coupons on alumina risers placed in the furnace for heat treating (not to scale).

Tensile coupons were placed vertically and close to each other near the center of the furnace and supported on risers to ensure an even anneal. Type K thermocouples were positioned underneath the samples and between the alumina risers to monitor and control the actual temperature of the anneal.

Tensile Testing of Annealed Samples

Coupons of Ti-6Al-4V were tested on an Instron 5584 tensile tester according to standard ASTM E-8 using a load cell of 150 kN (33,000 lb) (Figure 12).

Figure 12: Instron 5584 tensile test machine in the Cal Poly Materials Engineering Department.

Each test was grouped in fours with two rates of strain. The first rate, known as "ramp 1," was 1 mm/min. After an elongation of 1.5%, the rate of strain changed to "ramp 2" at 5 mm/min. An extensometer was used to accurately monitor the first 1.5% strain. During ramp 2, the extensometer was removed and the Instron 5584 measured the remaining strain.

Metallography

Samples used for metallographic imaging were selected to show greatest potential difference in micrographs. Tensile coupons from 1200°F (648°C) and 1450°F (787°C), both furnace cooled and air cooled were selected. Each sample was sectioned using a diamond wafering blade and mounted using diallyl phthalate resin. Samples were ground and polished to a 0.5 micron finish with diamond solution and etched using Kroll's reagent. Microstructures were examined to note any significant change in grain size or phase morphology.

Results

Furnace Survey and Testing

The maximum service temperature of the Fisher Scientific basic muffle furnaces according to the official manual is 1125°C (2057°F). Heating should take no more than two hours to reach assigned temperatures. During testing, the furnaces reached a maximum of 793°C (1459°F) after three hours. The furnaces were not working to specifications.

After looking into the problem, it was found that heating elements of the furnace were faulty and damaged. Replacement of the heating elements and removal of deposits in the furnace allowed for the furnace to return to normal operating specifications.

The comparison of the furnace's built-in thermocouple and temperature display to an outside thermocouple and data logger is seen in Table I.

Table I: Temperature Readings of Furnace Survey

Furnace Temperature (°C)				
Display	1	2	3	4
648	640	630	647	637
676	663	647	671	659
704	691	675	700	687
732	721	707	727	717
760	750	744	750	748
787	775	762	780	771

Points nearest to the center of the furnace floor, 1 and 3, show the closest actual temperature to what the display reads on the furnace. Points 2 and 4 near the back of the furnace show colder regions by as much as 18°C (40°F). The result is a localized region in the center of the furnace that measures within 5°C (20°F) of the display value (Figure 13).

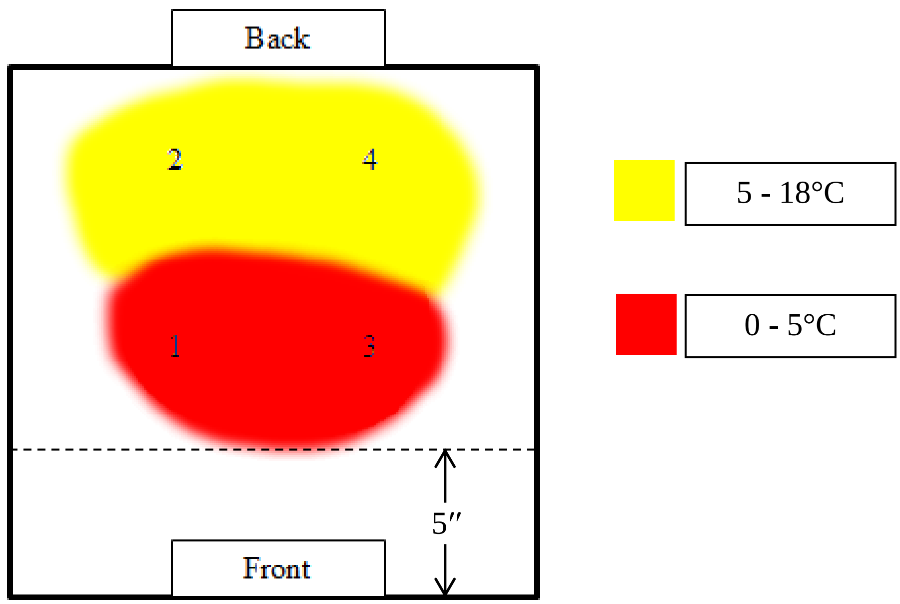

Figure 13: Temperature distribution compared to display setting.

The furnace survey measures how accurately the furnace can reach and maintain a given temperature. The first five inches from the front of the furnace was not surveyed as heating near the furnace door will produce much lower temperatures than the furnace set-point.

This test suggested that any annealing should be located close to the center of the furnace and monitored with an outside thermocouple and data logger to remove any error from the display controls of the furnace.

Heat Treatment Cooling Curves

Furnace cooled samples cooled from the annealing temperature to 427°C (800°F) within 60 to 80 minutes of shutting off the furnace power. Thermal measurements were recorded every 10 minutes. Data points were recorded in Microsoft Excel to produce a graph of temperature versus time and a best fit line was found to offer a cooling rate in °F/min (Figure 14).

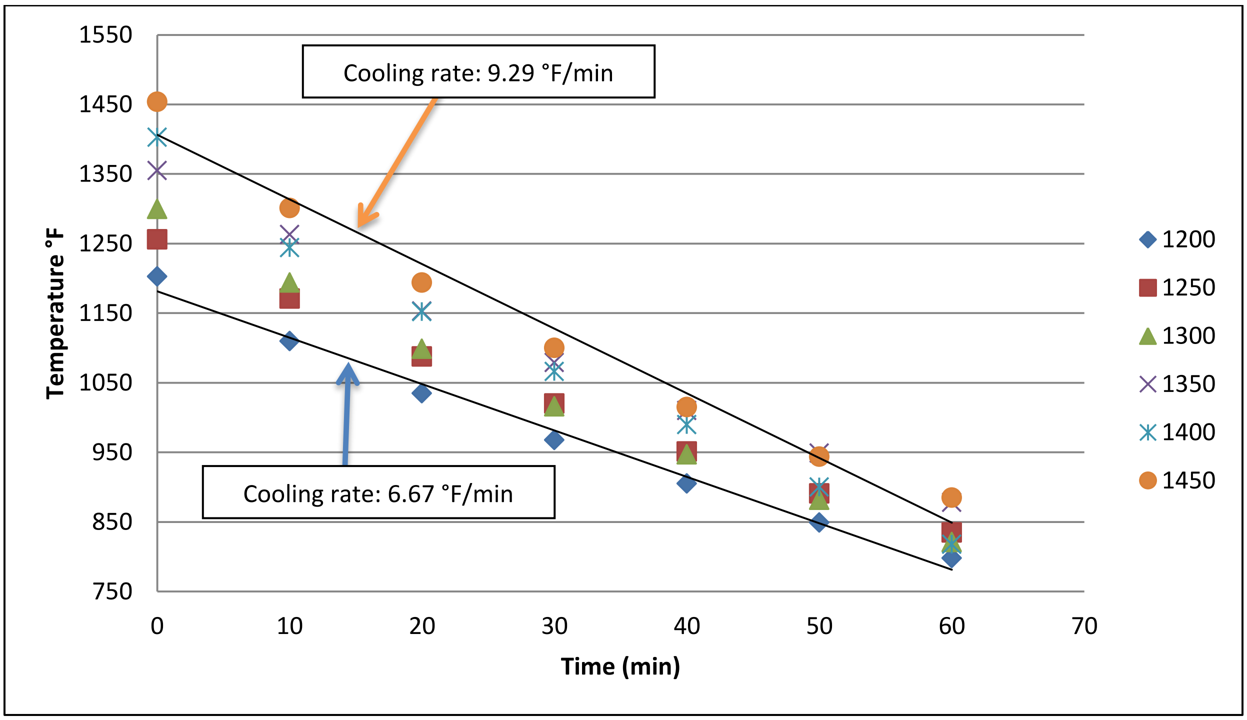

Figure 14: Cooling rates of furnace cooled Ti-6Al-4V.

All samples cooled within 60 to 80 minutes at varying cooling rates. The lowest cooling rate measured using a best fit line was 6.67 °F/min for the furnace cooled 1200°F annealed samples. The highest cooling rate measured using a best fit line was 9.29 °F/min for the furnace cooled 1450°F annealed samples. The air cooled samples did not have their cooling rates monitored.

Alpha Case

As a result of annealing, a thin layer of alpha case formed on the surface of the samples. The preliminary micro sample that offered the worst case scenario showed a depth of alpha case of 25 microns (0.001 in) (Figure 15).

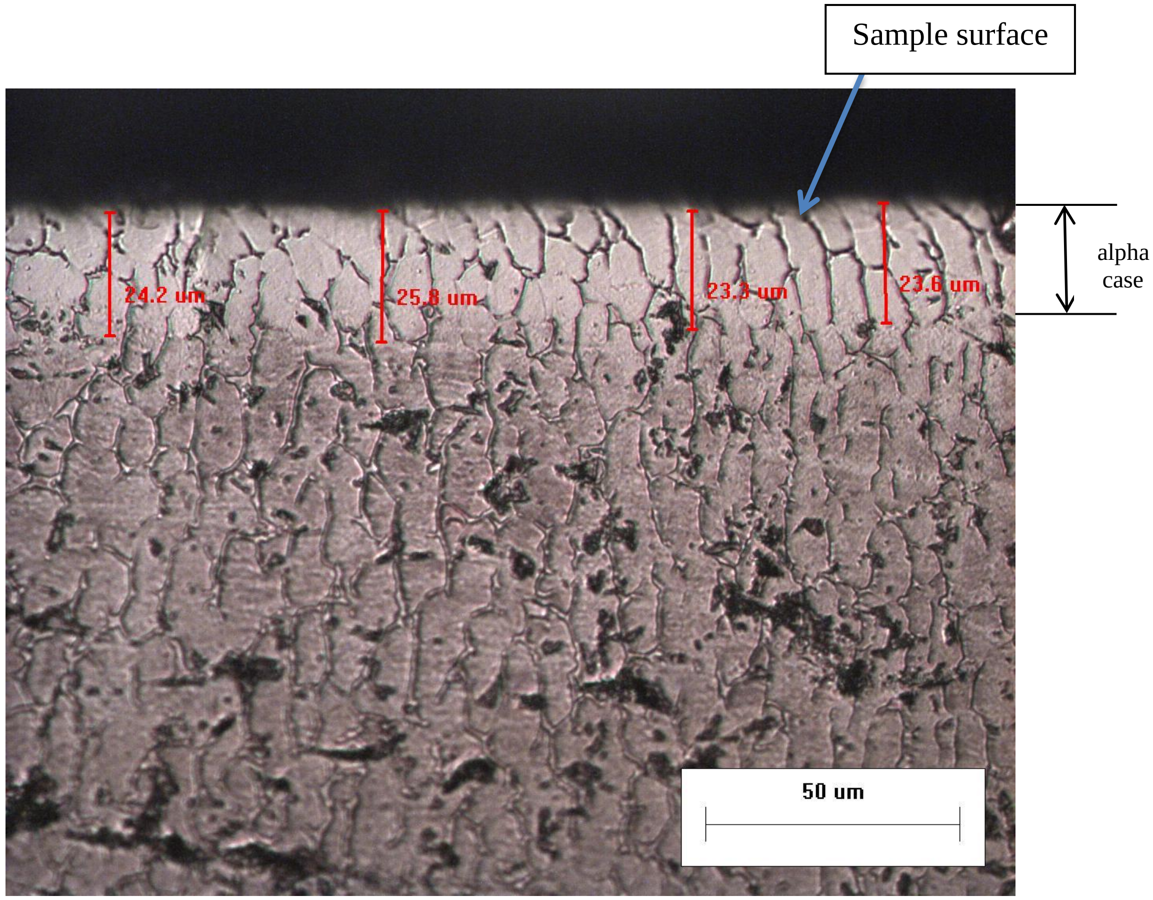

Figure 15: Alpha case and associated measurements on the surface of an annealed sample of Ti-6Al-4V.

Removal of alpha case would require surface grinding. However, due to budget constraints and lack of a surface grinder, this alpha case could not be removed. 25 microns of alpha case is the maximum depth to expect in these Ti-6Al-4V samples. A preliminary tensile test would have to be conducted to determine if the depth of alpha case would affect tensile tests.

Tensile Test Data

The first set of tensile tests determined if the greatest depth of alpha case affected the tensile coupons. The thickness of the samples was 0.250″ (6.35 mm). Alpha case at 0.002″ (50 microns), therefore, made 0.8% of the sample thickness. Testing the 1450°F furnace cooled samples, which had this visible layer of alpha case, proved to have no effect on the tensile strength of the material (Figure 16).

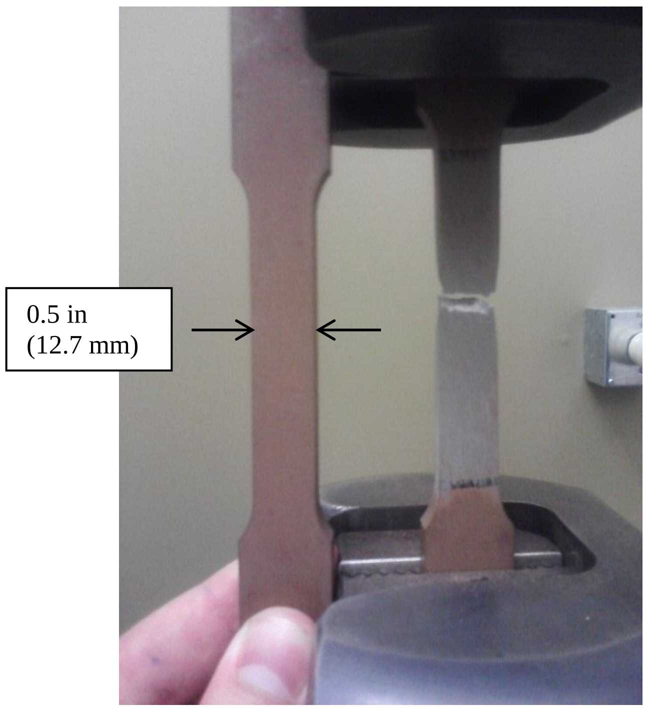

Figure 16: Tensile coupons of Ti-6Al-4V before and after tensile test.

During testing, alpha case would loosen and flake off from the gauge length and spalls off the surface during failure.

Tensile data was compared with the AMS 6931 standard for mill annealed Ti-6Al-4V. Mill annealed Ti-6Al-4V, according to this standard, has an ultimate tensile strength of 896 MPa (130 ksi) and a 0.2% offset yield strength of 827 MPa (120 ksi).[8]

ANOVA statistical analysis was used to compare the ultimate tensile strengths of air cooled and furnace cooled samples. A table of ultimate tensile strength for furnace cooled samples of Ti-6Al-4V across annealing temperatures was produced (Table II).

Table II: Ultimate Tensile Strength across Annealing Temperatures for Furnace Cooled Samples

Temp (°F)	1200	1250	1300	1350	1400	1450
Sample 1	935.9	969.7	930.3	933.4	923.2	919.4
Sample 2	915.0	926.5	919.0	923.2	925.0	930.5
Sample 3	913.6	922.6	932.3	916.4	917.7	919.0
Sample 4	916.6	939.6	914.3	923.3	948.1	902.6

Two box plots were formed that show the distribution of tensile strength across the annealing temperatures and cooling rates. There is a wide distribution in ultimate tensile strength for the furnace cooled samples, but a narrow distribution of means (Figure 17).

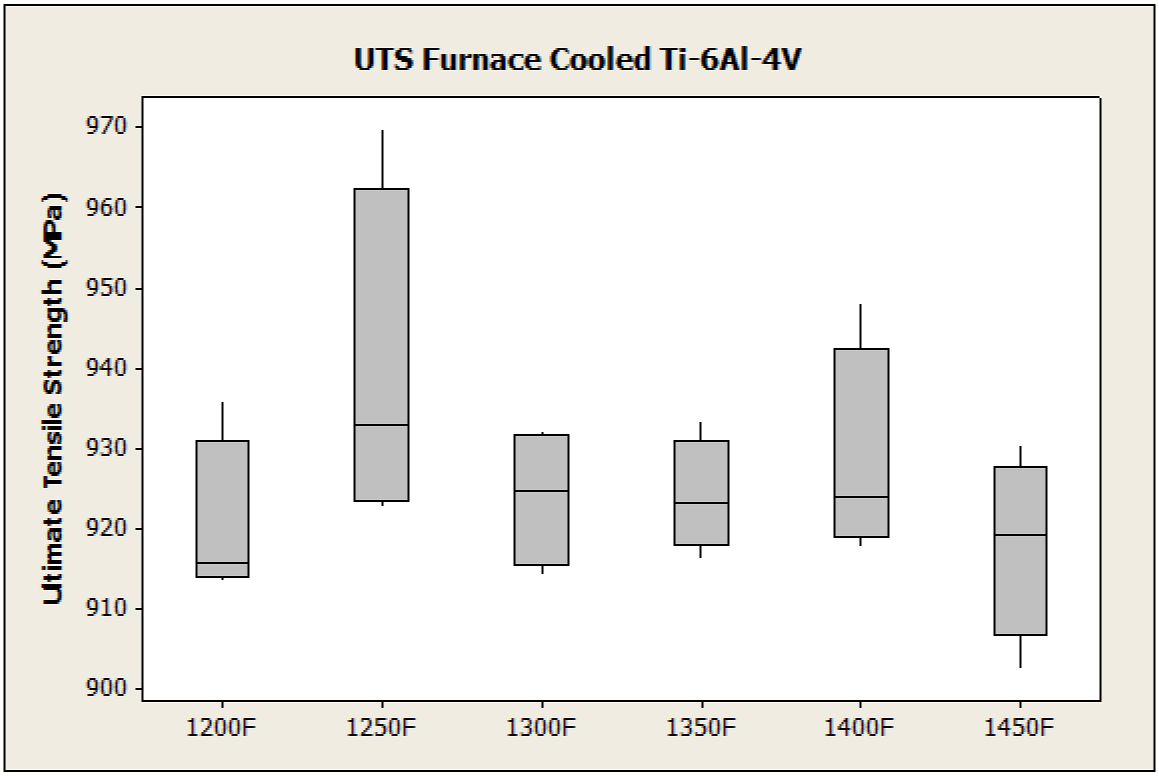

Figure 17: Box plot distribution of the ultimate tensile strengths of furnace cooled samples.

The means across these annealing temperatures are within 20 MPa (3 ksi) of one another and have a grand mean of 926 MPa (134 ksi). Tukey pair-wise comparisons made with a 95% confidence interval showed no statistical differences between furnace cooled samples (Appendix A).

Air cooled samples show a small increase in tensile strength compared to the furnace cooled samples. A table of ultimate tensile strength for air cooled samples of Ti-6Al-4V across annealing temperatures was produced (Table III).

Table III: Ultimate Tensile Strength across Annealing Temperatures for Air Cooled Samples

Temp (°F)	1200	1250	1300	1350	1400	1450
Sample 1	947.7	928.7	942.8	927.8	938.9	945.4
Sample 2	937.2	939.7	922.8	934.0	949.2	962.3
Sample 3	926.6	929.2	928.9	925.2	936.0	942.3
Sample 4	926.0	927.5	936.6	924.7	957.2	946.5

The lower annealing temperatures, between 1200°F and 1350°F, have similar results to the furnace cooled samples with tensile strength means within 10 MPa (1.5 ksi) of one another and an average of 930 MPa (135 ksi) tensile strength (Figure 18).

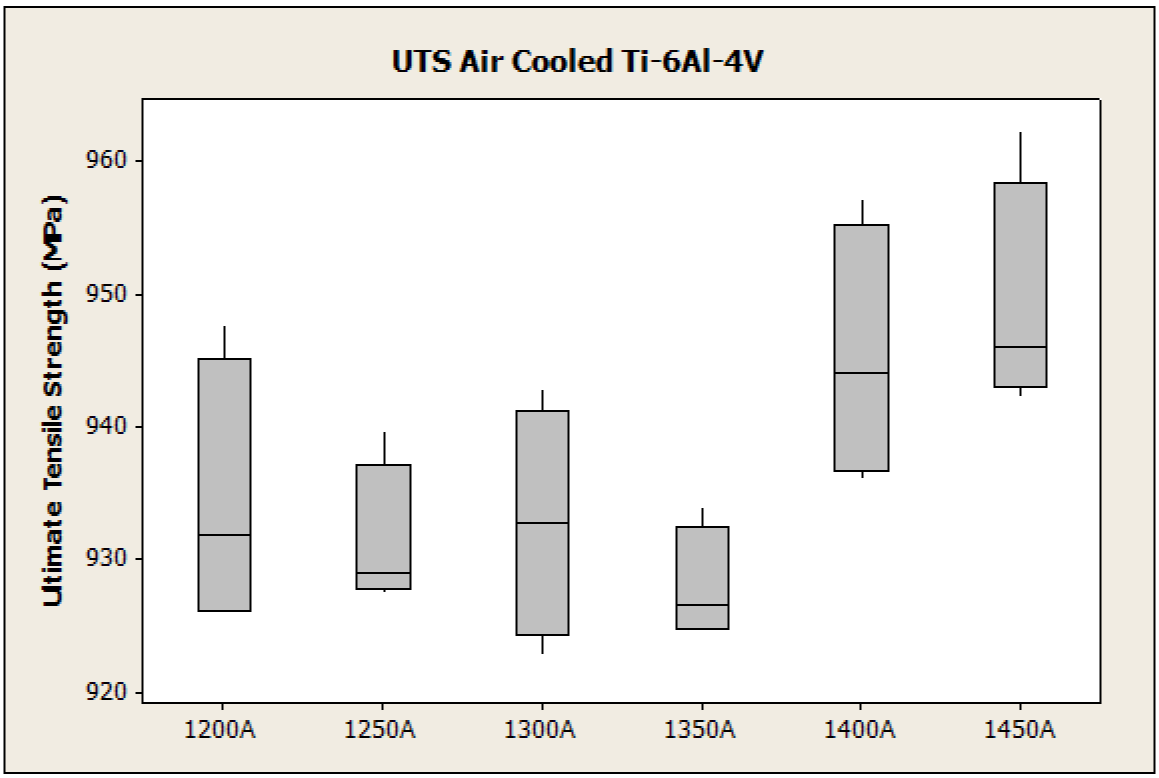

Figure 18: Box plot distribution of the ultimate tensile strengths of air cooled samples.

Tukey pair-wise comparisons made with a 95% confidence interval showed a statistically significant difference between 1450°F samples and 1350°F samples (Appendix B).

Yield strength showed a decreasing trend for both air cooled and furnace cooled anneals. The furnace cooled samples had 0.2% offset yield strengths ranging from 896 MPa (130 ksi) to 876 MPa (127 ksi). Air cooled samples ranged from 890 MPa (129 ksi) to 850 MPa (123 ksi). Weber Metals desires increases in both tensile strength and yield strength. However, standards show only minimum values for UTS and yield strength. Differences of up to 40 MPa, or 7 ksi, may be deemed negligible.

Metallography

The as-received micro sample from Weber Metals shows equiaxed grains of α-phase with a transformed β-phase. This is expected as hot forged mill annealed parts have equiaxed grains (Figure 19).

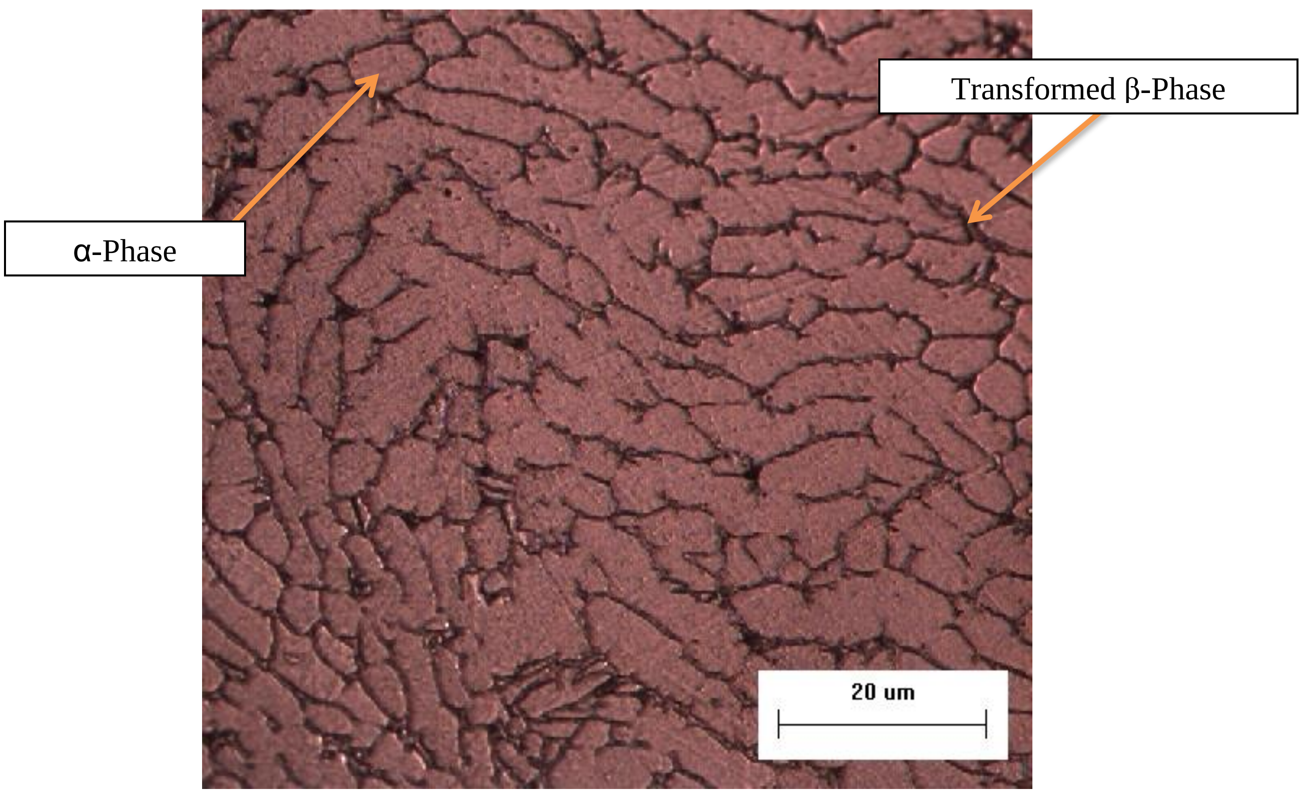

Figure 19: Micrograph of mill annealed Ti-6Al-4V at 500x magnification etched using Kroll's reagent.

The β-phase settles along the grain boundaries of equiaxed α-phase. Annealing relieves residual stresses in the material and influence grain recrystallization and growth in hot worked materials. Since we were not expecting a significant change in microstructure and found little difference in the resulting tensile strengths, the annealing and cooling “ends” of the project were examined for metallography.

The 1200°F air cooled and furnace cooled micrographs also show equiaxed α-phase with a transformed β-phase at the grain boundaries (Figure 20).

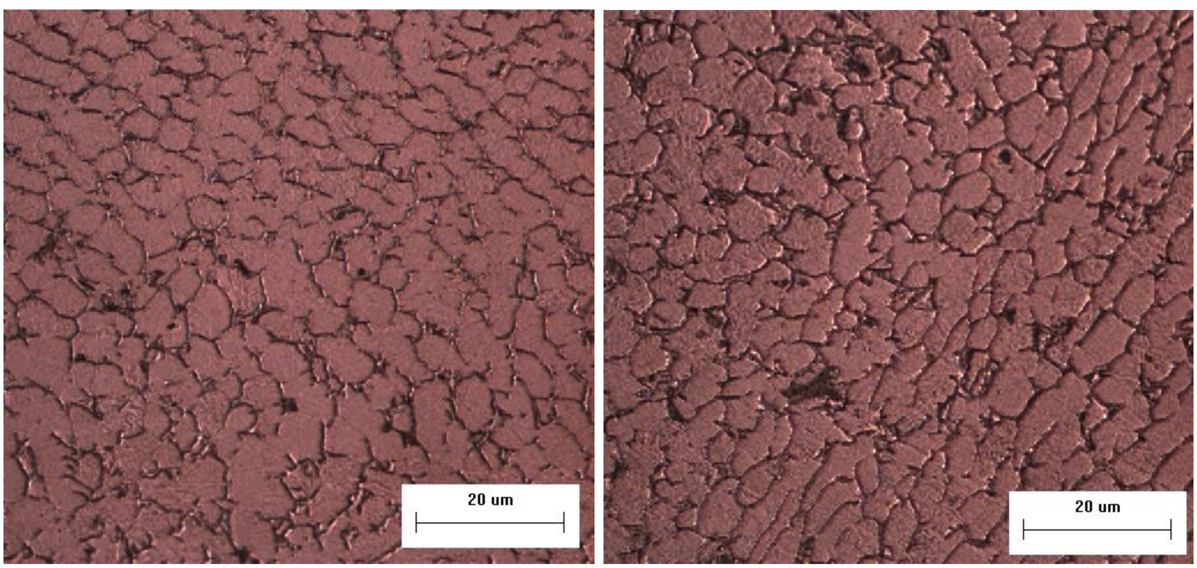

Figure 20: Micrographs of 1200°F Ti-6Al-4V at 500x magnification. Furnace cooled (left), air cooled (right). Etched using Kroll’s reagent.

There is still evidence of grain orientation that came from hot working during forging, much like the as-received sample. This microstructure further supports the insignificant change in tensile strength.

The 1450°F air cooled and furnace cooled micrographs also show equiaxed α-phase with a transformed β-phase at the grain boundaries (Figure 21).

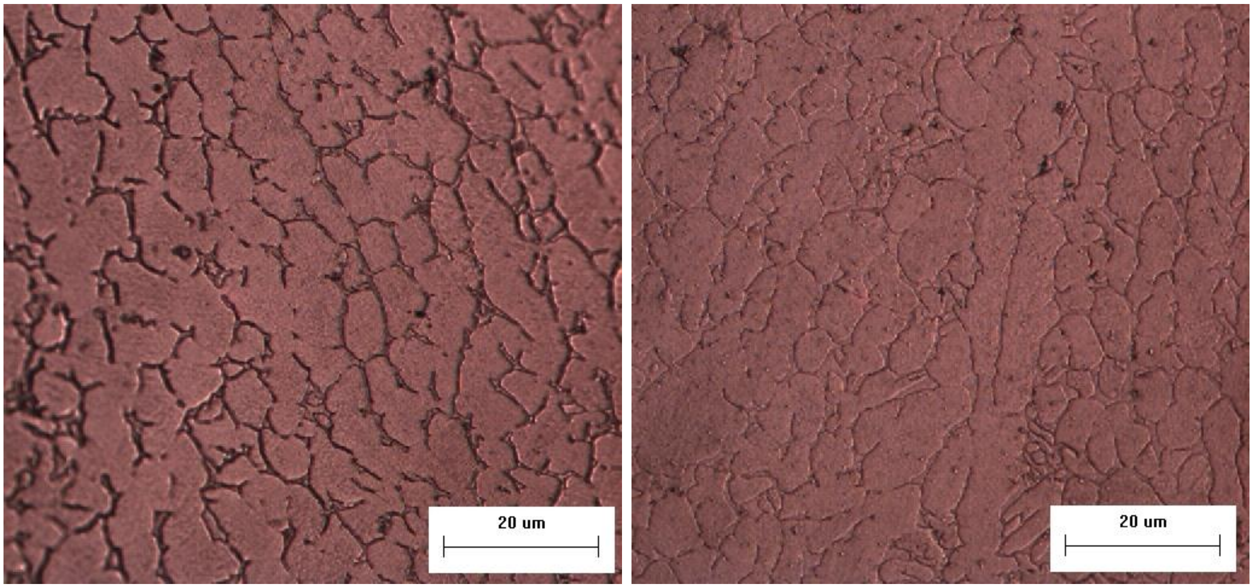

Figure 21: Micrographs of 1450°F Ti-6Al-4V at 500x magnification. Furnace cooled (left), air cooled (right). Etched using Kroll's reagent.

There is evidence of grain growth on these two micrographs. The lighter grain boundary on the 1450°F air cooled, which experienced the highest cooling rate, may suggest a different ordering of titanium.

Discussion

Heat Treatment

Annealing of Ti-6Al-4V in its α + β phase field just below its martensitic starting temperature should have little effect on the microstructure as mentioned in the Introduction. However, as the material is heated to the α + β phase field, one expects some partial reversion of alpha to beta.

This beta brought about by these annealing processes will affect the tensile strength of the material by the way it cools. Quenching the material should form a version of α′ martensite whereas slow cooling would ease the β-phase back into α-phase. Having martensite in the microstructure along the grain boundaries should show marked increase in tensile strength. Continuing documentation of cooling rates from these annealing temperatures can lead to a threshold or limit where one can control the microstructure of the transformed β phase. Cooling rates beyond the scope of this project should yield higher tensile strengths.

Tensile Testing

As per the cooling rates associated with the temperatures between 1200°F and 1450°F, there has been a slight increase in tensile strength compared to the AMS 6931 standard. However, the standards hold minimum values which may cover the recorded differences of 40 MPa, or 7 ksi. In the effect that these values are higher than the maximum documented value for tensile strength and yield strength, one would have to decide if 40 MPa, or 7 ksi, is worth putting more products through heat treatments. Putting into perspective that 40 MPa is just over a 4% increase in strength.

Metallography

The micrographs appear the same at 500x magnification. Resulting similarities in tensile strengths support the micrographs. The higher tensile strength associated with the highest cooling rate could yield a different transformation of the β-phase resulting in a different ordering of titanium. Performing x-ray diffraction (XRD) or electron dispersive spectroscopy (EDS) could identify the composition of the transformed β-phase at the grain boundaries.

Conclusions

1. Annealing mill annealed Ti-6Al-4V between 1200°F and 1450°F for 1 hour offers no significant change in tensile strength.

2. Annealing mill annealed Ti-6Al-4V between 1200°F and 1450°F for 1 hour offers little change in microstructure.

3. Performing XRD or EDS could identify the composition of the transformed β-phase

Acknowledgements

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Appendix A: Statistical Comparison of Tensile Data for Furnace Cooled Samples

One-way ANOVA: Furnace Cooled Samples

```
Source  DF    SS   MS     F      P
Factor   5  1192  238  1.43  0.263
Error   18  3009  167
Total   23  4201

S = 12.93   R-Sq = 28.37%   R-Sq(adj) = 8.47%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -------+---------+---------+---------+--
1200F  4  920.26  10.46   (---------*--------)
1250F  4  939.63  21.35                (--------*--------)
1300F  4  923.98   8.72      (--------*--------)
1350F  4  924.09   7.02      (--------*--------)
1400F  4  928.49  13.43         (--------*--------)
1450F  4  917.88  11.49  (--------*--------)
                         -------+---------+---------+---------+--
                              915       930       945       960

Pooled StDev = 12.93
```

Grouping Information Using Tukey Method

```
       N    Mean  Grouping
1250F  4  939.63  A
1400F  4  928.49  A
1350F  4  924.09  A
1300F  4  923.98  A
1200F  4  920.26  A
1450F  4  917.88  A

Means that do not share a letter are significantly different.


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 99.48%


1200F subtracted from:

        Lower  Center  Upper  -------+---------+---------+---------+--
1250F   -9.66   19.36  48.39               (--------*---------)
1300F  -25.31    3.71  32.74          (--------*---------)
1350F  -25.20    3.82  32.85          (--------*---------)
1400F  -20.80    8.22  37.25           (---------*--------)
1450F  -31.41   -2.38  26.65        (--------*---------)
                              -------+---------+---------+---------+--
```

```
                                   -30         0        30        60


1250F subtracted from:

        Lower  Center  Upper  -------+---------+---------+---------+--
1300F  -44.68  -15.65  13.38    (---------*--------)
1350F  -44.57  -15.54  13.49    (---------*--------)
1400F  -40.17  -11.14  17.89      (--------*---------)
1450F  -50.77  -21.74   7.28  (---------*--------)
                              -------+---------+---------+---------+--
                                   -30         0        30        60


1300F subtracted from:

        Lower  Center  Upper  -------+---------+---------+---------+--
1350F  -28.92    0.11  29.14         (---------*---------)
1400F  -24.52    4.51  33.54           (---------*--------)
1450F  -35.12   -6.09  22.93       (---------*---------)
                              -------+---------+---------+---------+--
                                   -30         0        30        60


1350F subtracted from:

        Lower  Center  Upper  -------+---------+---------+---------+--
1400F  -24.63    4.40  33.43           (--------*---------)
1450F  -35.23   -6.20  22.82       (---------*---------)
                              -------+---------+---------+---------+--
                                   -30         0        30        60


1400F subtracted from:

        Lower  Center  Upper  -------+---------+---------+---------+--
1450F  -39.63  -10.60  18.42      (--------*---------)
                              -------+---------+---------+---------+--
                                   -30         0        30        60
```

Appendix B: Statistical Comparison of Tensile Data for Air Cooled Samples

One-way ANOVA: Air Cooled Samples

```
Source  DF      SS     MS     F      P
Factor   5  1423.3  284.7  4.20  0.011
Error   18  1220.2   67.8
Total   23  2643.5

S = 8.233   R-Sq = 53.84%   R-Sq(adj) = 41.02%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -+---------+---------+---------+--------
1200A  4  934.38  10.27         (-------*--------)
1250A  4  931.28   5.66      (-------*--------)
1300A  4  932.79   8.74       (--------*-------)
1350A  4  927.92   4.24  (--------*--------)
1400A  4  945.33   9.71                  (-------*--------)
1450A  4  949.13   8.98                     (--------*--------)
                         -+---------+---------+---------+--------
                         920       930       940       950

Pooled StDev = 8.23
```

Grouping Information Using Tukey Method

```
       N     Mean  Grouping
1450A  4  949.130  A
1400A  4  945.325  A B
1200A  4  934.378  A B
1300A  4  932.795  A B
1250A  4  931.283  A B
1350A  4  927.925    B

Means that do not share a letter are significantly different.


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons

Individual confidence level = 99.48%


1200A subtracted from:

         Lower  Center   Upper    +---------+---------+---------+---------
1250A  -21.579  -3.095  15.389             (--------*---------)
1300A  -20.066  -1.583  16.901              (--------*--------)
1350A  -24.936  -6.453  12.031            (--------*--------)
1400A   -7.536  10.947  29.431                    (--------*---------)
1450A   -3.731  14.752  33.236                      (--------*---------)
                                  +---------+---------+---------+---------
                                -40       -20         0        20
```

```
1250A subtracted from:

         Lower  Center   Upper    +---------+---------+---------+---------
1300A  -16.971   1.512  19.996                (--------*--------)
1350A  -21.841  -3.358  15.126             (--------*---------)
1400A   -4.441  14.043  32.526                      (--------*--------)
1450A   -0.636  17.847  36.331                        (--------*--------)
                                  +---------+---------+---------+---------
                                -40       -20         0        20


1300A subtracted from:

         Lower  Center   Upper    +---------+---------+---------+---------
1350A  -23.354  -4.870  13.614            (---------*--------)
1400A   -5.954  12.530  31.014                     (--------*---------)
1450A   -2.149  16.335  34.819                       (--------*--------)
                                  +---------+---------+---------+---------
                                -40       -20         0        20


1350A subtracted from:

        Lower  Center   Upper    +---------+---------+---------+---------
1400A  -1.084  17.400  35.884                       (---------*--------)
1450A   2.721  21.205  39.689                         (---------*--------)
                                 +---------+---------+---------+---------
                               -40       -20         0        20


1400A subtracted from:

         Lower  Center   Upper    +---------+---------+---------+---------
1450A  -14.679   3.805  22.289                 (--------*--------)
                                  +---------+---------+---------+---------
                                -40       -20         0        20
```